

## EXOTIC SEARCHES AT LEP

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In the last five years, the operation of the LEP accelerator has provided the HEP community with a unique opportunity to search for physics beyond the standard model at the typical energy scale of 200 GeV. Although most of the data analysis has been focused on the traditional sectors of Higgs and gravity-mediated SUSY physics, a considerable effort has been dedicated by ALEPH, DELPHI L3 and OPAL to the search for more exotic physics scenarios, which go from gauge-mediated supersymmetry breaking, to compositeness, to gravitational extra-dimensions. This talk reviews the latest experimental results on a selection of final states which are believed to be of particular interest for exotic physics or which present some anomaly in the data with respect to standard model expectations.

### 1 Introduction: searches for new physics at LEP

At LEP the strategy adopted to look for signals of new physics can vary, depending on the physics case, between two extreme approaches.

One extreme possibility is to perform what is normally called an *indirect* search, which consists in measuring with the best possible accuracy some reference standard model processes and comparing the obtained cross sections with the standard model expectations. Any disagreement beyond the experimental uncertainty is interpreted as evidence for new physics. This approach does not require the definition of a precise theoretical framework alternative to the standard model, but it offers poor experimental sensitivity (a few hundred fb for LEP2 luminosities) because these processes have typically large cross sections in the standard model. Examples of this search strategy are the precise measurements of di-fermion or di-boson production cross sections, with or without initial state photons.

In order to improve the statistical sensitivity a better signal/background ratio is needed, which in turn requires a more precise definition of the signal to search for, with a consequent loss of generality. This approach is followed, for example, in supersymmetry (SUSY) searches, where the signal sensitivity reaches the level of a few tens of fb at LEP, but the result is strictly valid only in the context of the chosen theoretical framework. The very extreme case of this *direct* approach is the search for the standard model Higgs, for which the theoretical model is completely defined, apart from the Higgs mass. Here very specific analyses have reached sensitivities of some 10 fb.

Despite the fact that most searches have focused on the SM Higgs and MSSM-SUGRA sectors, a considerable effort has been dedicated by ALEPH, DELPHI, L3 and OPAL to the search for more exotic scenarios, which go from gauge-mediated supersymmetry breaking, to compositeness, to gravitational extra-dimensions. Since an exhaustive review of all these results would be impossible in this context, only a selection of a few final states will be discussed in detail, which are believed to be particularly powerful in the search for new physics or that present some anomaly in the data compared to standard model expectations. For this purpose, Table 1 has been prepared which describes the correlation between a given final state and the exotic models that this final state can probe. The

table shows that, indeed, the simplest final states, such as  $e^+e^- \rightarrow f\bar{f}(\gamma)$  or  $e^+e^- \rightarrow \gamma(\gamma) + E_{\text{miss}}$ , can probe the largest number of models. These and some other channels will be discussed in the following sections.

Table 1: Sensitivity of the final states investigated at LEP for exotic physics.

	Contact Int.	Z'	Extra-dim.	GMSB SUSY	Mass. sgoldstino	Spont. RpV SUSY	RpV SUSY	Technicolor	Excited fermions	Anom. coupl.	New fermions	FCNC	LeptoQuarks
single- $\gamma$	X	X	X	X		X		X	X	X			
Non-pointing single- $\gamma$				X									
$\gamma\gamma E_{\text{miss}}$				X					X	X			
$\gamma\gamma(\gamma)$	X		X		X				X	X			
$ll(\gamma)$	X	X	X				X	X	X				
$jj(\gamma), gg\gamma$	X	X	X		X			X		X			
$\tau\tau E_{\text{miss}}$				X		X							
$j\bar{j}l E_{\text{miss}}$									X		X		X
$j\bar{j}j\bar{j}, b\bar{j}j\bar{j}, b\bar{b}j\bar{j}$							X	X				X	
$b\bar{j}l E_{\text{miss}}$							X					X	X
$j\bar{j} E_{\text{miss}}$													X
$ll E_{\text{miss}}$				X					X				
$j\bar{j}l\bar{l}$													X
$WW(\gamma), ZZ, Z\gamma$			X					X		X			
$Z E_{\text{miss}}$			X										
multi-l, multi-j							X						
$ll\gamma\gamma E_{\text{miss}}$				X					X		X		
multi-l $E_{\text{miss}}$				X									
“kinked” tracks				X							X		
heavy stable ptes				X							X		

Unless differently specified, the results mentioned in the this paper refer to the data collected by ALEPH, DELPHI, L3 and OPAL in the year 2000 at centre-of-mass energies ranging from 202 GeV to 209 GeV and with a total integrated luminosity of about 220 pb<sup>-1</sup> per experiment. All results are preliminary.

## 2 Indirect searches with $e^+e^- \rightarrow l^+l^-(\gamma)$ final states

The most important reference process for indirect searches is the charged lepton pair-production, possibly accompanied by initial state radiation:  $e^+e^- \rightarrow l^+l^-(\gamma)$ . Anomalies in the measured cross section can indicate the existence of new interactions between the initial and final state fermions, such as the exchange of new heavy particles like new vector bosons (Z'), gravitons (G) or heavy sneutrinos ( $\tilde{\nu}$ ). When the exchanged particles are *extremely* heavy, the interaction becomes essentially point-like (*contact-interaction*), and is described by effective lagrangian terms of the type:

$$\mathcal{L} \approx \frac{g^2}{\Lambda^2} (\bar{e}\gamma^\mu e)(\bar{f}\gamma_\mu f). \quad (1)$$

In equation 1 the  $\Lambda$  term (squared) in the denominator is necessary to compensate the dimension-six operator of the 4-fermion interaction and describes, in some universal way, the typical energy scale of the new interaction, in exactly the same way as the Fermi constant  $G_f^{-1/2}$  represents the energy scale of weak interactions in the Fermi model.

No evidence for anomalies has been found in the data collected by LEP in the year 2000, as well as in the samples collected in the previous years. Only OPAL<sup>1</sup> reports of a possible  $e^+e^- \rightarrow \tau^+\tau^-\gamma$  excess at  $\sqrt{s} > 200$  GeV at a level of 2.5  $\sigma$ . The excess is not confirmed by the other experiments<sup>2,3,4</sup>

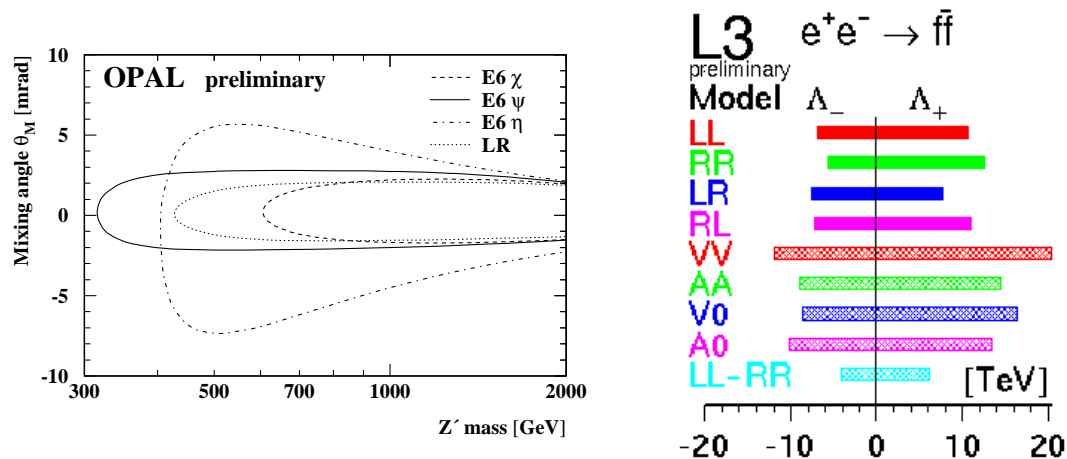


Figure 1: Left: OPAL results on the search for  $Z'$ . Right: L3 limits on 4-fermion contact terms in various theoretical frameworks.

and should be interpreted as a statistical fluctuation. Limits have been derived on the  $Z'$  mass as a function of the mixing angle with the standard model  $Z$  and on the  $\Lambda$  scale associated to 4-fermion contact-interactions. Some OPAL<sup>1</sup> and L3<sup>4</sup> results are shown in Figure 1; the other experiments present similar results<sup>2,3</sup>.

### 3 Search for new physics in single-photon events

In the standard model single-photon events are produced mainly via the process  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ , where the photon is emitted from the initial state electrons or from the  $W$  exchanged in the  $t$ -channel (for  $e^+e^- \rightarrow \nu_e\bar{\nu}_e\gamma$  only). Compared to the study of charged fermion-pair production discussed in the previous section, single-photon events present two distinctive features:

1. neutrinos cannot be produced via  $s$ -channel photon exchange so the standard model cross section is lower than  $e^+e^- \rightarrow f^+f^-\gamma$  in some phase space regions;
2. the final state is purely neutral and is thus sensitive to the production of new stable neutral particles  $X$  via  $e^+e^- \rightarrow X\gamma$  or  $e^+e^- \rightarrow XX\gamma$  processes (majorons, heavy neutrinos, gravitons, gravitinos, neutralinos,...).

Deviations can be searched for in the photon energy and angular distributions. For example, some SUSY models with light gravitinos<sup>5</sup> and some models with gravitational extra-dimensions<sup>6</sup> predict an excess of events with low photon energy (particularly at small polar angle).

The combined single-photon missing-mass spectrum observed by the four LEP collaborations in all LEP2 data ( $130 \leq \sqrt{s} \leq 209$  GeV)<sup>7</sup> is shown in Figure 2, where it is compared to a simulation of the standard model background. Discrepancies are visible below the  $Z$  peak, where a deficit of some 5% is seen, and at very low photon energies, where an excess of some 5% is observed. Unfortunately, these results cannot be interpreted as evidence of new physics such as GMSB or extra-dimensions, since the *shape* of the standard model simulation shown in Figure 2 is affected by a systematic uncertainty of order 5%, evaluated on the basis of the discrepancies between the two most used generators: Koralz<sup>8</sup> and Nunugpv<sup>9</sup>. More detailed investigations show that:

1. the deviation is observed consistently by all four experiments, although it is particularly evident in L3 results<sup>10</sup>;
2. the deviation does not have an evident dependence on the centre-of-mass energy;
3. the Nunugpv generator seems to fit the data fairly well, while the largest disagreement is observed with respect to Koralz.

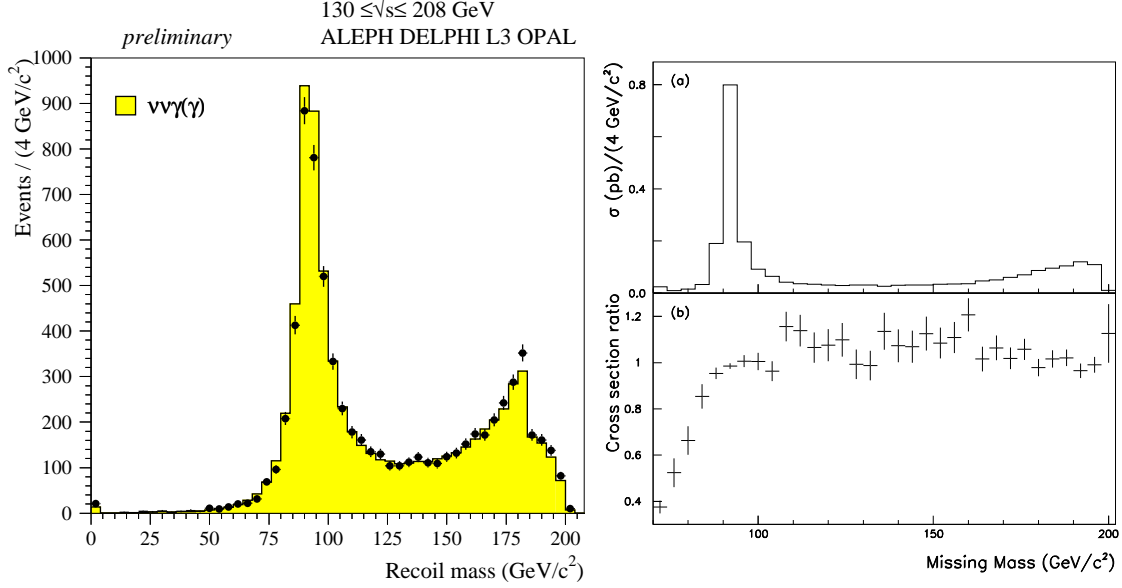


Figure 2: Left: LEP2 combined missing mass distribution in single-photon events. Right: Ratio between KK and Nunugpv expectations.

A third generator, KK<sup>12</sup>, not publicly available at the time of the conference, will soon replace Koralz. A preliminary comparison with Nunugpv, performed by the ALEPH Collaboration<sup>11</sup>, shows a better agreement than between Koralz and Nunugpv, apart from a limited region immediately below the Z return peak (Figure 2 Right).

For this channel, final conclusions will be drawn only after KK-based simulations will be available to all four collaborations.

#### 4 Multi-photon final states

One particular multi-photon final state has revealed to be of particular importance for exotic searches at LEP:  $e^+e^- \rightarrow \gamma\gamma E_{\text{miss}}$ , often addressed as “acoplanar-photons”. This is the ideal channel to look for evidence of GMSB<sup>13</sup> with neutralino-NLSP via the process  $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{g}\tilde{g}\gamma$ . The light gravitinos escape detection and the photons appear as acoplanar. Other exotic processes investigated with the same final states are, for example, the presence of anomalous 4-vector boson couplings and excited neutrino pair-production (in case of  $\nu^* \rightarrow \nu\gamma$  decay).

In this channel no anomalies are observed with respect to Koralz or Nunugpv (Figure 3 Left), given the large statistical uncertainty affecting the data, and limits on new physics are derived. The limit obtained by the L3 Collaboration on the  $\tilde{\chi}_1^0$  mass<sup>10</sup> is shown in Figure 3 (Right) as a function of the selectron mass (which determines the  $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{g}\tilde{g}\gamma$  cross section via t-channel exchange) and excludes, once for all, the GMSB scenario suggested by one  $ee\gamma\gamma E_{\text{miss}}$  event collected by the CDF experiment at Fermilab in 1996<sup>14</sup>. Similar limits are obtained by the other LEP collaborations<sup>11,15,16</sup>.

The result in Figure 3 (Right) is valid for light gravitinos, with masses of order 100 eV or smaller. For larger  $\tilde{g}$  masses, the decay  $\tilde{\chi}_1^0 \rightarrow \tilde{g}\gamma$  would have measurable lifetime and would produce events with photons which do not originate from the beam interaction region. As an example, the DELPHI cross-section limit for this process is shown as a function of the neutralino mean decay path in Figure 4 (Left).

#### 5 Acoplanar (kinked) leptons

Searches for GMSB in case of lepton-NLSP are based on the analysis of events with acoplanar lepton pairs. As for the  $\tilde{\chi}_1^0$ -NLSP case the lifetime  $\tau(\tilde{l} \rightarrow l\tilde{g})$  is a function of the gravitino mass squared. Depending on  $m_{\tilde{g}}$  one expects final states with simple acoplanar leptons ( $\tau < 1$  mm), tracks with

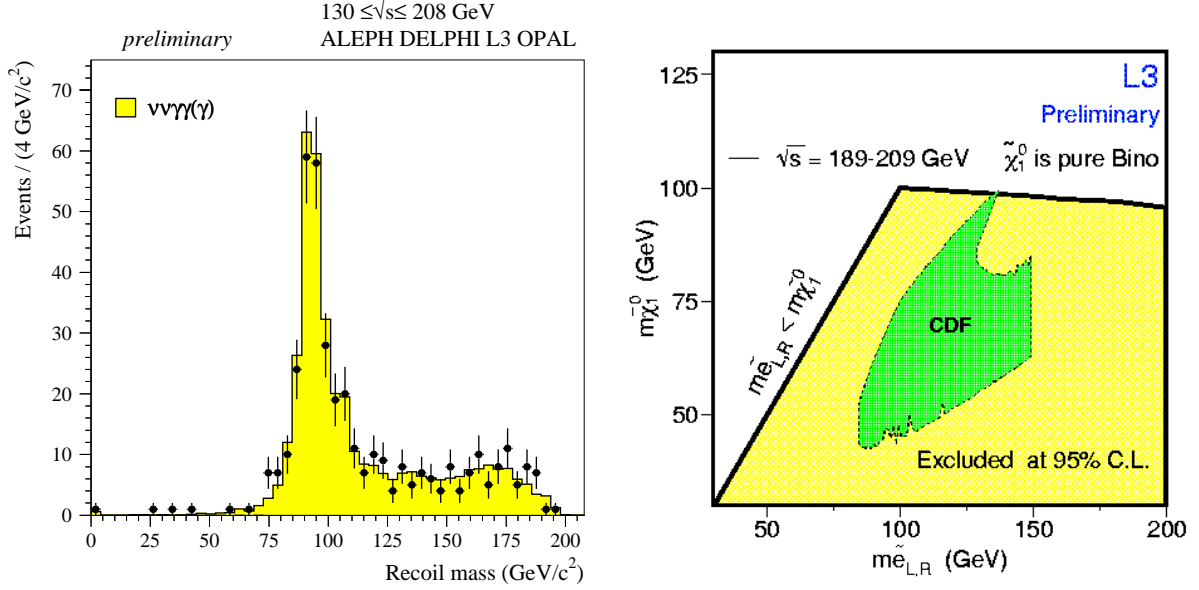


Figure 3: Left: Combined LEP missing mass distribution in events with acoplanar photon pairs. Right: Exclusion limit obtained by the L3 Collaboration in the  $(m_{\tilde{\chi}_1^0}, m_{\tilde{e}})$  plane assuming  $\text{BR}(\tilde{\chi}_1^0 \rightarrow \tilde{g}\gamma) = 100\%$ . The region allowed by the CDF  $ee\gamma\gamma E_{\text{miss}}$  event is now excluded.

visible impact parameter ( $1 \text{ mm} < \tau < 1 \text{ cm}$ ), tracks with a decay kink in the tracking devices ( $1 \text{ cm} < \tau < 1 \text{ m}$ ), or heavy stable charged particles ( $\tau > 1 \text{ m}$ ).

No evidence for any of these processes has been observed at LEP. The limit obtained by ALEPH<sup>11</sup> on the stau mass as a function of the stau lifetime is shown in Figure 4 (Right).

## 6 Final states with two jets and a photon

Theories with light gravitinos also predict the existence of sgoldstinos ( $\Phi$ ), the goldstino superpartners, which have arbitrary mass<sup>21</sup>. Being superpartners of a supersymmetric particle, sgoldstinos have even R-parity and do not need to be produced in pairs so the largest cross section is expected for the process  $e^+e^- \rightarrow \Phi\gamma$ . Sgoldstinos decay into gluons (dominant) or photons.

A search for sgoldstino has been recently performed by the DELPHI Collaboration<sup>22</sup>. The key distribution is the mass recoiling the photon in jet-jet- $\gamma$  final states ( $e^+e^- \rightarrow \Phi\gamma \rightarrow gg\gamma$ ), which is shown in Figure 5 (Left) for the data sample  $189 < \sqrt{s} < 208$  GeV. No evidence for a signal is observed. The tiny peak at  $m_{jj} \sim 115$ , which might indicate exotic Higgs production via  $e^+e^- \rightarrow H\gamma$ , was seen in 1999 data and not confirmed by 2000 data.

The same  $jj\gamma$  final state can be used to search for Technicolor ( $e^+e^- \rightarrow \rho_T\gamma \rightarrow jj\gamma$  or  $e^+e^- \rightarrow \phi_T^0\gamma \rightarrow jj\gamma$ ), whose minimal version is excluded by LEP1<sup>23</sup> but which still survives in non-minimal versions (walking technicolor)<sup>24</sup>. Even in this second case,  $\rho_T$  masses below 200 GeV are excluded by LEP2 data<sup>28</sup>.

## 7 Four-jet final states

To extend the LEP sensitivity for  $\rho_T$  masses above 200 GeV the analysis of four-jet final states is used, assuming  $m_{\pi_T} < \sqrt{s}/2$ . Four-jet events are probably the most deeply studied final state at LEP2, given its importance for Higgs searches and W physics. Still, LEP results in this topology have always been somehow controversial, especially for the difficulties associated to the choice of the correct jet-pairing in the estimation of the jet-jet invariant masses. The first anomalies in four-jet events were observed by ALEPH in 1995<sup>25</sup>, but disappeared with larger statistics. In 1999 DELPHI<sup>26</sup> and L3<sup>27</sup> also observed some (weak) excess over the background estimations in 4-jet events having jet-jet invariant mass close to 68 GeV. Although the analyses assume different physics scenarios (Technicolor searches

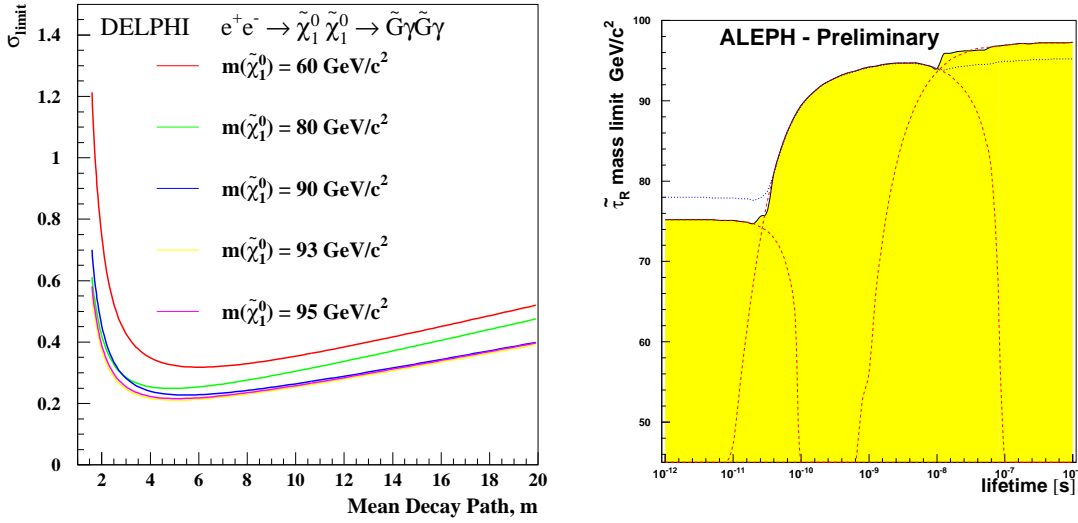


Figure 4: Left: Exclusion limit obtained by the DELPHI Collaboration on  $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma\tilde{G}\gamma)$  as a function of the  $\tilde{\chi}_1^0$  decay path. Right: Aleph exclusion limit on the stau-NLSP mass in GMSB as a function of the stau lifetime.

for DELPHI, charged Higgs searches for L3) the final state is similar and the excess is localised in the same jet-jet invariant mass region (Figure 6). By adding the data collected in 2000 the DELPHI anomaly disappears<sup>28</sup>, while the L3 peak is confirmed and reaches a final significance of 4.4 standard deviations<sup>29</sup>. Since ALEPH<sup>30</sup> and OPAL<sup>31</sup> do not observe any anomaly with similar analyses, this L3 result has to be interpreted either as a statistical fluctuation, which is unlikely given the significance, or as a spurious effect of the analysis.

## 8 Final states with jets and leptons

Among final states containing jets and leptons, the  $e^+e^- \rightarrow \text{j}bW$  channel deserves some comments since it is relatively new at LEP. An excess in  $e^+e^- \rightarrow \text{j}bW$  events could indicate anomalous single-top production, via  $e^+e^- \rightarrow t\bar{t}/t\bar{t}$  processes, as predicted by several exotic scenarios, from models with anomalous Z couplings<sup>17</sup>, to theories with dynamical ew-symmetry breaking<sup>18</sup>, to SUSY with R-parity violation (RpV).

Unfortunately, no evidence for any excess is observed in the data. The results are thus expressed as limits for anomalous Z couplings<sup>19</sup> (Figure 5 Right) or for the top decay width via neutral currents:  $\text{BR}(t \rightarrow Zu/Zc) < 17\%$ <sup>20</sup>. It's interesting to notice that, by exploiting the kinematic features of the signal at LEP (the top is produced almost at rest in the laboratory frame), the experimental sensitivity is comparable to that of Tevatron experiments.

## 9 Multi-lepton, multi-jet final states

Multi-particle final states are the ideal environment to search for SUSY with R-parity non-conservation. The number of different event topologies studied by the four LEP collaborations is impressive and gives an idea of the global effort dedicated to the search for new physics. Indeed, excellent agreement is observed between data and background expectations, with, maybe, one exception: OPAL data in the  $e^+e^- \rightarrow \tau^+\tau^- + \leq(4 \text{ jets})$  channel at  $\sqrt{s} \geq 206.5 \text{ GeV}$ <sup>16</sup>. Here 8 events are seen while 2.2 are expected from standard model sources, which corresponds to a Poisson probability of  $2 \cdot 10^{-3}$ . A similar analysis ( $e^+e^- \rightarrow \tau^+\tau^- + 4 \text{ jets}$ )<sup>32</sup>, performed by the ALEPH Collaboration, yields 6 (9) events with a background of 8.0 (5.0) at  $\sqrt{s} > 205.5 \text{ GeV}$  ( $\sqrt{s} < 205.5 \text{ GeV}$ ): if there's an excess this is concentrated at lower centre-of-mass energies according to ALEPH, which somehow contradicts the OPAL anomaly.

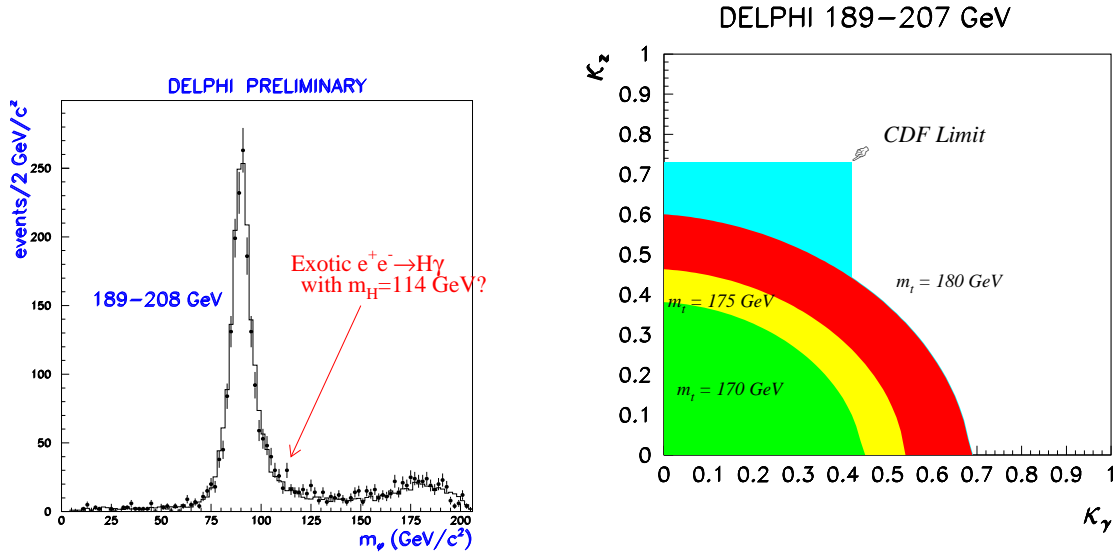


Figure 5: Left: Invariant mass distribution of the two jets recoiling the isolated photon in  $jj\gamma$  events in DELPHI. Right: Exclusion limit in the  $(\kappa_\gamma, \kappa_Z)$  plane set by DELPHI from the study of  $jbW$  final states (compared to a CDF limit).

## 10 Conclusions

The last year of LEP operation has been extremely successful for what concerns luminosity and beam energy: more than  $200 \text{ pb}^{-1}$  of data at centre-of-mass energies between 202 and 209 GeV have been collected, exceeding even the more optimistic expectations. Despite the large statistics accumulated and the huge effort dedicated by ALEPH, DELPHI, L3 and OPAL to search for any possible discrepancy with the standard model in any final state topology, no real evidence for exotic physics has been found. Only two channel still offer some matter of discussion, namely single-photon events, where a better control of the theoretical uncertainties is needed, and 4-jet final states, where a possible signal of charged Higgs production reported by L3 is not confirmed by the other experiments.

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## DELPHI preliminary

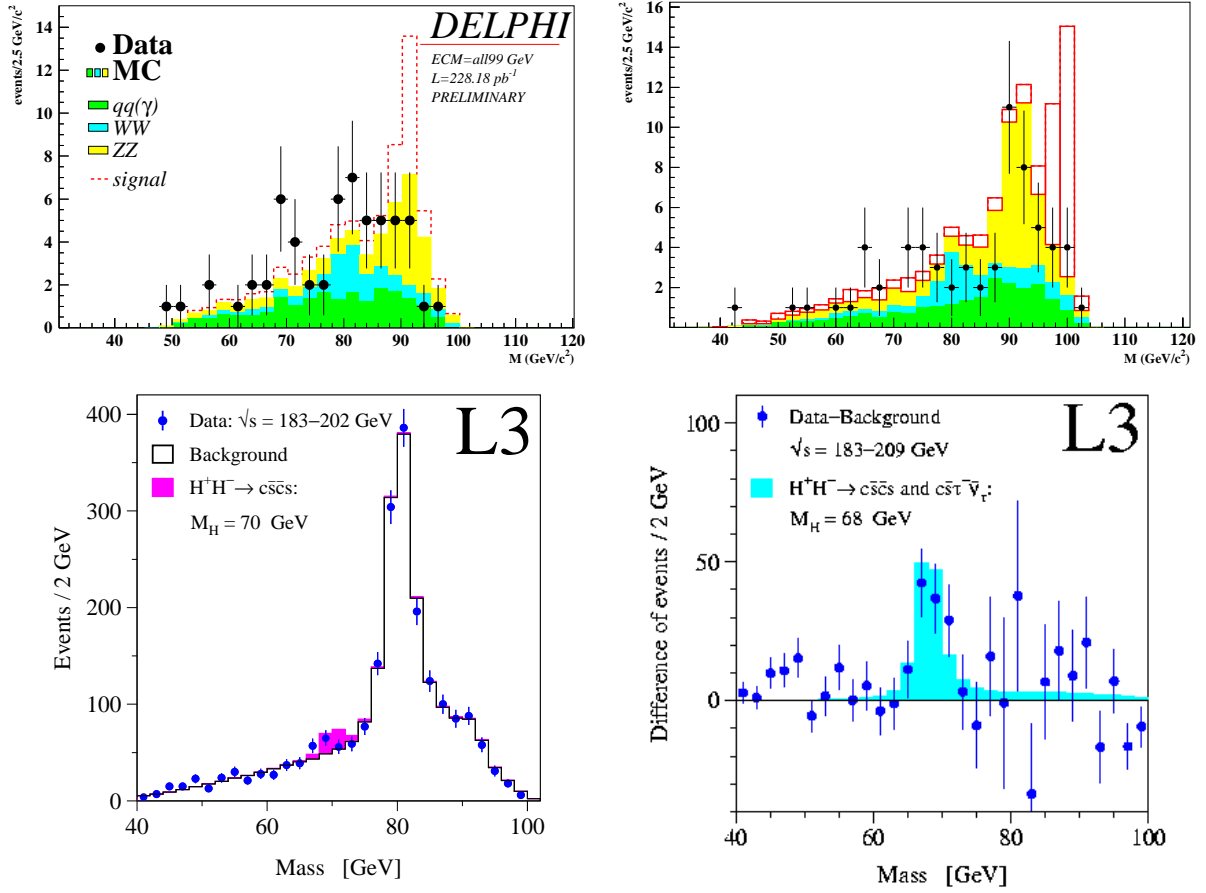


Figure 6: Top: The anomalous peak observed by DELPHI in 4-jet events in 1999 (Left) disappears with the 2000 update (Right). Bottom: L3 confirms the 1999 data anomaly (Left) with 2000 data (Right).

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